

EARTHQUAKE !

Yellowstone's Living Geology • by Wm. A. Fischer



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Front Cover Illustration: Earthquake Fissures
near Firehole Lake, Yellowstone National Park
National Park Service Photo

Cover design by Bill Chapman

EARTHQUAKE!

Highlights of Yellowstone Geology
With an Interpretation of the 1959
Earthquakes and their Effects in
Yellowstone National Park

by William A. Fischer

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PREFACE

The geologic history of an area is inevitably assembled by the labors of a number of geologists dedicated to the search for the truth as they walk plateaus, climb mountains and descend into canyons to decipher the fascinating story of earth history.

The complexities of Yellowstone geology are staggering to the professional and bewildering to the layman. In the pages that follow I have attempted to condense pertinent highlights of the past 70 million years as they relate to an understanding of earthquakes as a normal geologic process in Yellowstone National Park.

For those interested primarily in the earthquake changes there is included a map keyed to the text and with it one can reconstruct the sequence of events that began on the night of August 17, 1959.

ACKNOWLEDGEMENT

I am under many obligations, notably to my associates Park Naturalists M. D. Beal, G. D. Marler, and A. T. Hewitt who have read portions of the manuscript and kindly offered words of criticism and encouragement.

The drafting and illustrations were very capably executed by the talented hand of Bill Chapman; Mrs. Helen G. Minish typed the manuscript.

Dr. Stephen W. Nile, Collaborator in Seismology for the U. S. Coast and Geodetic Survey, Butte, Montana, has been most cooperative in supplying seismic data from his personal files and has faithfully answered the many questions with which I have besieged him in recent months.

For information on the Yellowstone rhyolite plateau I am deeply indebted to Dr. F. R. Boyd of the Geophysical Laboratory of the Carnegie Institute, Washington, D. C., who has graciously permitted the inclusion of some of his unpublished research.

Correspondence and conversations with Dr. Irving J. Wit-kind of the U. S. Geological Survey and Dr. Kenneth L. Cook of the University of Utah are gratefully acknowledged.

Credit is given in the text to the various organizations and individuals who have permitted reproduction of photographic material.

A large portion of the chapter devoted to changes in geysers and hot springs is based upon the observations of Park Naturalist George D. Marler.

Park Naturalists A. Mebane, B. Watson, K. Higgins, R. Frisbee, W. Germeraad and Park Ranger R. McClelland worked through the winter months obtaining data on post-earthquake changes in geysers and hot springs. The detailed results of their observations will provide the basis of a future more technical report.

The entire earthquake research project, of which this is only a brief summary, was made possible by the National Park Service through the efforts of Superintendent Lemuel A. Garrison and Chief Park Naturalist Robert N. McIntyre. Colorado College granted me a leave of absence from my regular teaching duties to participate in the study.

To Robert McIntyre I am most grateful for a critical review of the completed manuscript. We have labored together in an attempt to bring into proper focus this most interesting of Yellowstone's newest attractions.

William A. Fischer
8 April 1960
Yellowstone Park, Wyoming

*"I have no doubt that if this part of the country should ever be settled and careful observations made, it will be found that earthquake shocks are of very common occurrence"*¹



PLATE 1. Earthquake Camp, near Steamboat Point, east side of Yellowstone Lake, so named from several earthquake shocks experienced at this place on the night of the 19th of August 1871. Photo by W. H. Jackson, Courtesy of the U. S. Geological Survey film library.

¹ F. V. Hayden, 1872. Preliminary Report of the United States Geological Survey of Montana and Portions of Adjacent Areas, Part 1, p. 82.

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INTRODUCTION

The 17th of August 1959 began as a typical day in Yellowstone National Park. Automobiles laden with vacationers from all parts of the United States passed steadily through the five entrances to the park, their occupants motivated by a strong desire to see and enjoy the marvels of nature that make this national park one of the wonders of the world.

By sunset 6,000 people had settled in the campgrounds, 8,000 had found lodging in the hotels and cabins. In addition some 4,000 employees of the concessioners and the National Park Service brought the population count to 18,000. It was a warm, clear moonlight night, unusually warm for this altitude, and as the evening activities ended, people wandered back to their quarters and prepared to settle down for the night. Little did they realize that events were taking place underground destined to make this a night to be remembered.

The Madison River, formed by the confluence of the Fire-hole and Gibbon Rivers, flows in a westerly direction out of Yellowstone Park toward the town of West Yellowstone, and then continues its journey in a northerly direction through Ennis, Montana, and on to its junction with the Missouri River. Twelve miles west of the park boundary an artificial dam impounds the waters to create Hebgen Lake and the shores of the lake and canyon are dotted with resorts, cabins, and campgrounds. For many of the inhabitants of the Madison Canyon the night of August 17th was to be a night of terror bringing death to nine and leaving at this date some 19 still considered missing.

At 11:37 P.M. M.S.T. a sudden displacement of rock occurred along a fault at a depth of ten miles beneath the earth's surface at $44^{\circ} 50' N.$ Latitude and $111^{\circ} 05' W.$ Longitude. Shortly following this displacement these events occurred in rapid succession. An estimated 43.4 million cubic yards of rock slid as a unit into the Madison Canyon burying the road and river under several hundred feet of rubble for a distance of a mile impounding the waters of the Madison River to create a second lake below Hebgen Dam. Hebgen Lake basin was tilted causing the south side to rise and the north side to depress resulting in oscillations of the lake surface that caused it to crest the dam four times and kept the surface in motion for a period of 11 hours.

Within the park rockslides buried many sections of the roads, buildings were damaged at Old Faithful and at Mammoth Hot Springs, and 298 geysers and hot springs erupted, 160 of which had no previous record of eruption. Nature was on a rampage and man's faith in **terra firma** was suddenly put to the supreme test.

As shock waves radiated out from the center of disturbance they were felt throughout an area of 500,000 square miles and recorded at seismograph stations around the world.

This earthquake with a magnitude of 7.1 on the Richter Scale has been equaled or exceeded only 14 times within recorded history in the United States.

The geologic phenomena of earthquakes, landslides, and volcanoes excite the layman and scientist alike because these are examples of dynamic earth processes. Within a matter of minutes more geologic changes occurred than would normally happen in several thousand years.

THE CAUSES OF EARTHQUAKES

Earthquakes are a common everyday event. About one million shocks are registered annually around the world, but of this number only a few are of strong intensity. One need only observe a mountain terrain to note that the uplift of mountains and plateaus, the offsetting of river courses, and other physiographic changes have been accompanied by shifts of the earth's crust resulting in earthquakes. These have been common happenings extending throughout geologic time. The planet we inhabit is a dynamic object. Gradational processes of weathering and erosion attempt to plane off the earth's surface to the ultimate base level of erosion which for all practical purposes may be regarded as sea level. From the Mississippi River Basin alone there is over one million tons of sediment removed and dumped into the Gulf of Mexico every twenty-four hours. Extend this erosion concept into the geologic past and one can see that the earth would have been base-leveled millions of years ago and the oceans would now cover the earth were there not restorative forces within that periodically rejuvenate the surface.

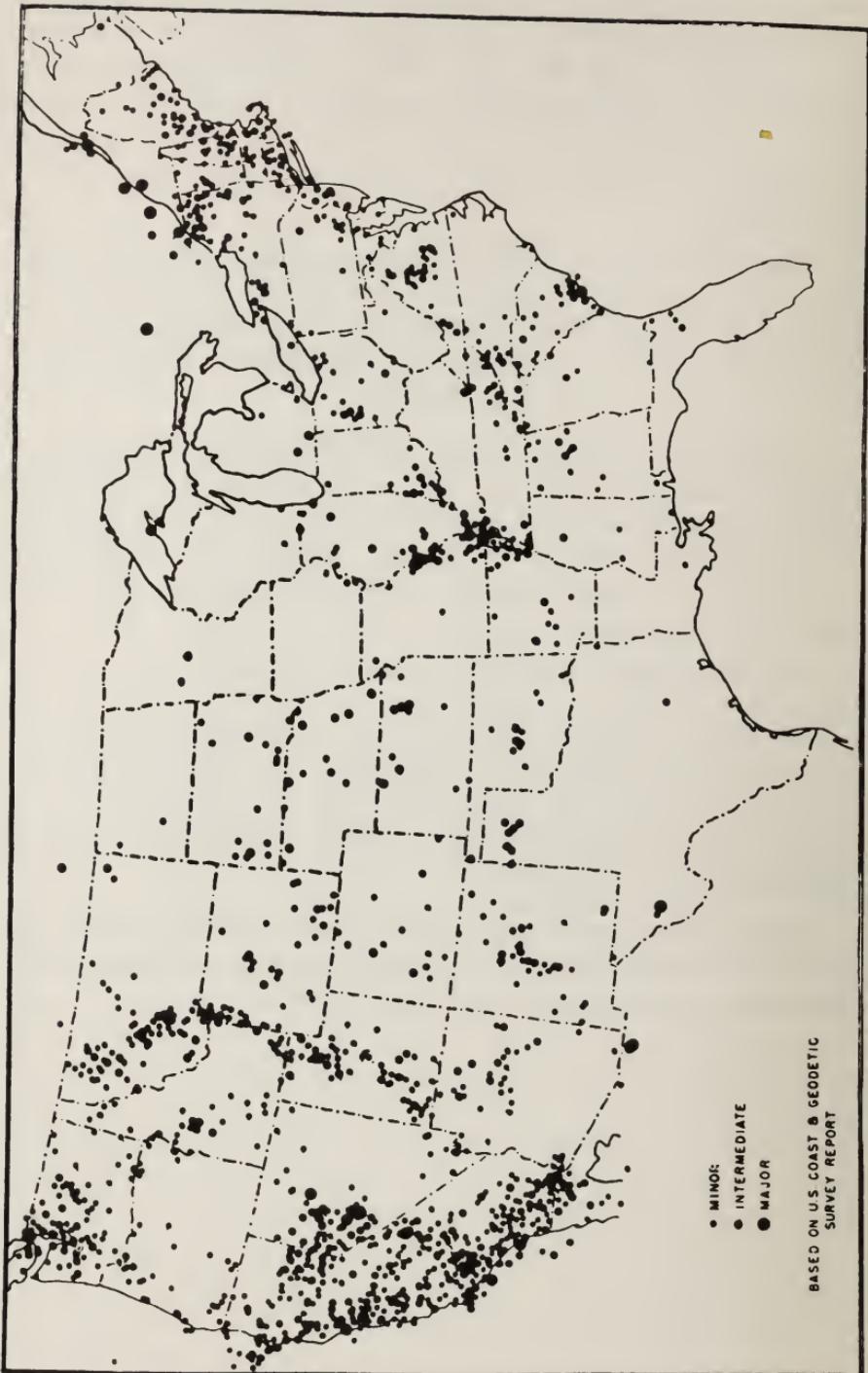
The ultimate source of these forces is still not entirely understood. Some geologists believe in the thermal contrac-

tion theory which implies that as the earth cools from its initial molten stage, the crust adjusts to the contracting core by wrinkling and fracturing. A comparison could here be drawn to the wrinkled skin of a dried apple. Other geologists favor the idea of convection currents rising from the earth's molten core and dragging down portions of the crust. When dragged horizontally the forces produce squeezing resulting in mountain building.

Regardless of the ultimate source of the force we know that this energy is transmitted into, and stored within, the rocks of the earth's crust. When these rocks are distorted beyond their limit of strength they yield suddenly along a fracture by a process known as faulting.

Yellowstone Park is situated in the Rocky Mountains. The Rockies consist of chain after chain of mountains that have been uplifted, folded and faulted extensively during the past 70 million years. Some of the chains are broad flexures with granite cores flanked by tilted layers of sedimentary rock. Others are composed largely of volcanic products. Faults of varying magnitude have been mapped throughout the mountain system. Many of these faults have been quiet during recorded human history, others have been active since the Pleistocene, and still others appear to have been dormant for millions of years. On some faults the movement has been largely vertical caused by tensile forces, on others a thrusting by compression is apparent.

Earthquakes in historic times have centered largely in areas of mountain building and their epicenters are frequently coincident with the position of known faults.



Reproduced by permission of G. P. Woollard (1957)

FIG. 1. Earthquakes in the United States through 1957

MECHANICS OF EARTHQUAKES

With the rupturing of rocks to create a fault, or with renewed movement along an old fault, the energy released travels away by means of waves. It is the motion of these waves rather than the displacement along the fault that usually causes the most damage. Movement of a few feet along a fault can cause extreme damage and maximum displacements in historic times have not exceeded fifty feet.

Seismologists recognize two main classes of earthquake waves; body waves which travel through the interior of the mass in which they are generated, and the surface waves which travel only along the surface.

Body waves of two types are generated by faulting. One is called the "P" or Primary wave which is a wave of alternate compression and rarification like a true sound wave in air. The "S", or Secondary wave vibrates perpendicular to the direction it is travelling. The behavior of the "P" wave could be likened to the movement of a billiard ball striking a line of billiard balls with each one passing on the energy of motion to its neighbor. The "S" wave is best compared to the undulatory motion imparted to a rope tied to a tree at one end and vigorously shaken at the other. The form and passage of the waves can be observed as they travel along the rope.



PLATE 2. Serpentine Fence west of Yellowstone along Highway 287.
Photo by J. P. Stacy, Courtesy of the U. S. Geological Survey
film library.

This "Serpentine Fence" is probably the result of compression, or it may represent the path taken by an "S" wave that was polarized horizontally. It would require a detailed study of the ground to know which is the true explanation.

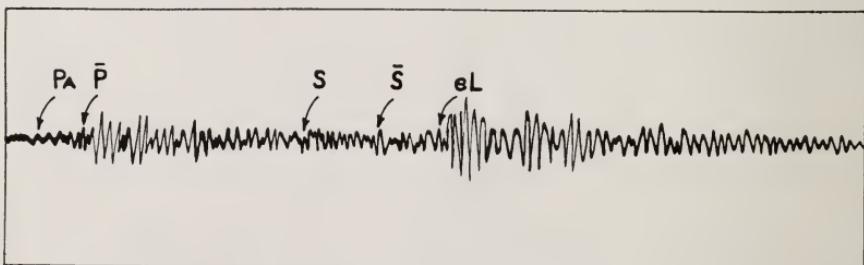
Surface waves known as "L" or Long waves, have an oscillatory motion similar in character to wave motion on a body of water. They are generated by the "P" and "S" waves directly above the focus of the earthquake and travel slowly around the world.

The names Primary, Secondary, and Long are suggestive of their relative speeds of transmission and arrival times at seismograph stations.

A seismogram is the graphic record of an earthquake recorded by an instrument known as a seismograph. Knowing the travel times of "P" and "S" waves through the different types of rock, it is possible to use the time factor of "S" minus "P" time to determine the distance of the earthquake from the recording station. Arcs of distance drawn from a number of seismograph stations intersect at a point on the earth's surface known as the epicenter.

Calculations of ground motion permit a determination of the earthquake's magnitude on the Richter Scale and field studies of earthquake damage are used to estimate intensity on the Modified Mercalli Scale.

FIG. 2 Seismogram of a Typical Aftershock as Recorded on August 18, 1959 at University of Utah Seismograph Station, Salt Lake City, Utah.



Reproduced by permission of U. S. Coast and Geodetic Survey

When the earth is at rest the seismograph traces a straight line on the graph. Earthquake vibrations result in oscillations which are traced by a beam of light or stylus on sensitized film. Note the sequence of arrivals of "P", "S" and "L" waves. Shocks from the Hebgen Lake area take less than one minute to reach the recording station at Salt Lake City, Utah. An earthquake in Japan would take from ten to twelve minutes to reach the same station.

On the night of August 17 we can visualize then an accumulation of energy being stored in the rocks of the earth's crust at a depth of ten miles below Grayling Creek along the western boundary of Yellowstone Park. Gradually the elastic limit of these rocks was exceeded, they ruptured, shock waves travelled out in all directions from the focus, some travelling through the earth and some around the surface. As these waves encountered rocks of different densities and old fault planes, they were reflected, refracted, and their paths and speeds altered accordingly. These vibrations set the atmosphere in motion generating sound waves, deep roaring sounds like the boom of distant artillery or the roar of a passing train or truck. Many observers noted the sounds and also described the strange sensation of seeing trees move when no wind was blowing.

The total energy release from this one earthquake was equal to that of about 200 atom bombs of the type dropped on Hiroshima, Japan. When making comparisons of this type it is well to keep in mind that with earthquakes the energy is unconfined and free to dissipate itself in all directions away from the focus.

Within Yellowstone Park there were extensive rockslides in the canyons, streams became turbid, and the ground water table was severely shaken causing drastic changes in the behavior of many hot springs and geysers. To properly interpret the cause of the earthquake and the geologic changes that have occurred, it is imperative that the reader have some appreciation of the geology of the region.

A GLIMPSE INTO THE PAST

Yellowstone has been described as a land of "living geology," a place where the people can see geologic processes in operation. Here one can enjoy the beauty of the landscape and see dramatic evidence of the slow incessant work of water, wind, heat and ice as each has played its part in creating, shaping and altering the land surface. Broad open plateaus, geyser basins, canyons and waterfalls all hemmed in by lofty snow-capped mountain peaks embracing a territory of 3,400 square miles. To the inquisitive park visitor the important question is, "why so much variety in this unique area?"

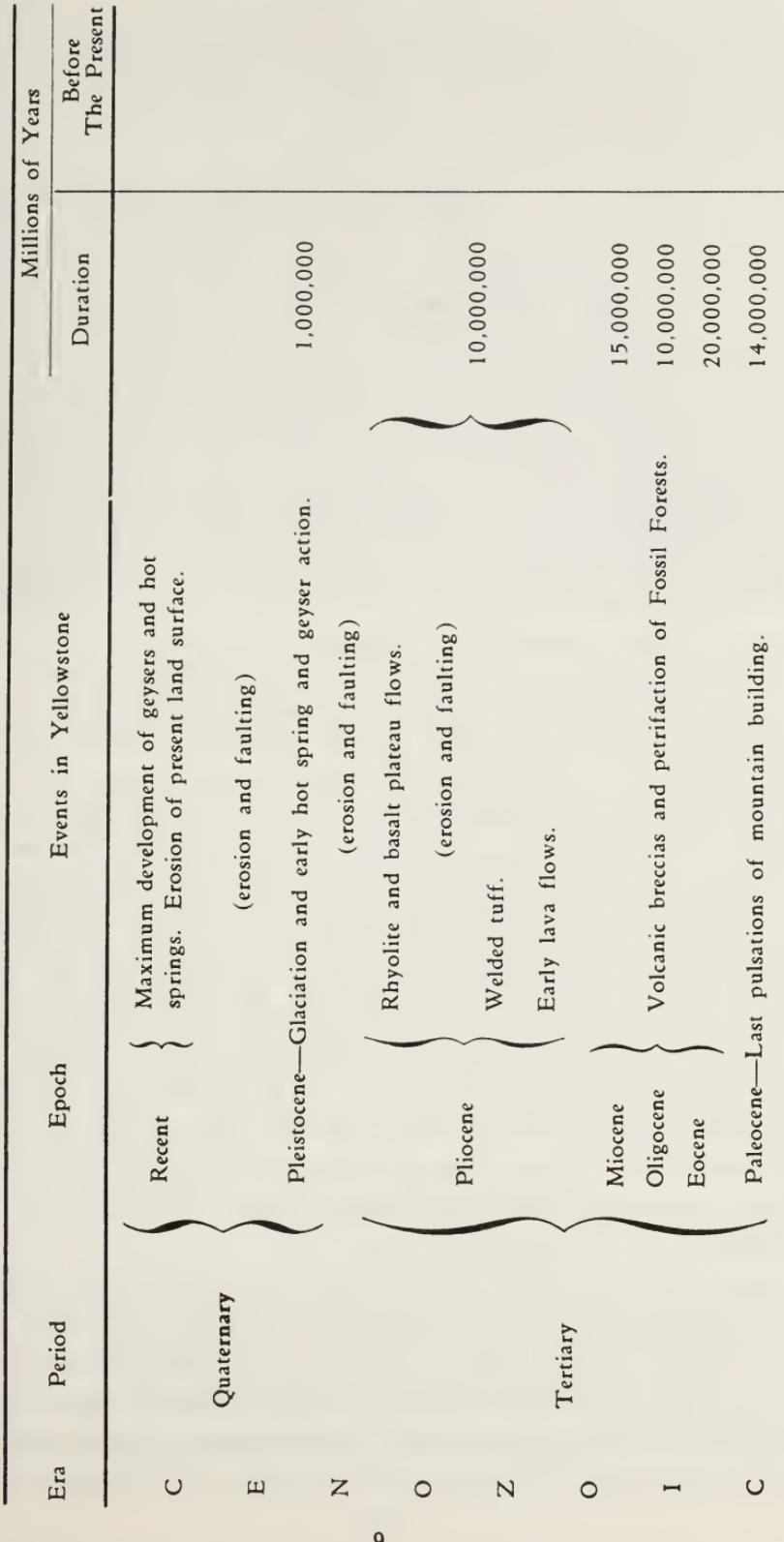
The answer can in part be found by travelling an imaginary pathway back in time. From astronomic calculations and the radiometric techniques of dating rocks the evidence now points toward a beginning point for the earth some five billion years in the past. Rocks formed since the inception of geologic processes on the earth are recognized within the different eras and periods of geologic time. To place events in their proper perspective we might imagine ourselves travelling backwards in time and walking at such a rate that we cover one thousand years with each pace. Two paces would take us to the dawn of the Christian era, 35 miles to the time when the rocks now exposed on Mt. Everts were being formed, 250 miles to the oldest sedimentary rocks exposed on the Northeast Entrance road, and if we continued the journey covering 1,000 years per pace we would walk in excess of 500 miles to reach the time when the granites of Hell Roaring Mountain were being formed.

Events that took place during these early formative years have been deciphered in the park, but the rocks formed at these times are largely obscured by later geologic formations. The layered rocks of the earth's crust can be compared to the pages of a manuscript, originally bound in proper sequence but later tattered and torn by mountain building processes so that in places entire chapters are missing and others are out of place.

It is the task of the geologist to decipher this jigsaw puzzle and reconstruct past events. Events of the past 70 million years have been most effective in determining the structural framework and topography that we view today and for these reasons we will pick up the sequence at this point.

FIG. 3.

CENOZOIC HISTORY OF YELLOWSTONE



EARLY MOUNTAIN BUILDING

The park when viewed from an airplane or a high mountain top, presents a broad flat plateau surface with an average elevation of 7,500 feet hemmed in by mountain ranges on three sides and open to the southwest. When placed in regional perspective Yellowstone is observed to fit into the general pattern of the Rocky Mountains where range after range follows a general northwest-southeast alignment. The lofty peaks of the Teton Range abut against the southern edge of the park, while the Snowy-Beartooth-Absaroka trend delineates the northern and eastern park boundaries. To the northwest the Gallatins rise above the plateau surface.

Mountains are ephemeral features in terms of geologic time. The poetic concept of "the eternal hills" is fine for a human life span but of course does not apply to geology.

Long before these mountains formed and for countless spans of time, much of the western United States was inundated by shallow arms of the ocean and in these downwarped areas great thicknesses of marine sedimentary rocks were deposited. Toward the end of the Cretaceous period, about 70 million years ago, a change began to take place and this region that had been submerged for so long a period of time began to feel the intensified pulse of the restless interior of the earth. The downwarp that had served as the repository for thick accumulations of stratified marine rocks was slowly subjected to compressive and vertical forces which initiated the gradual uplift of broad tracts of land destined by subsequent uplift and erosion to become the chains of mountains now included in the Rockies. With continued compression the formations yielded plastically to the deforming stresses until the rupture point was reached and then failure by faulting occurred. One can only speculate on the number of earthquakes that must have accompanied these times of mountain building!

In the pioneer days of the geological sciences investigators were hampered by a belief that the earth was not very old and consequently all of the observed crustal deformation had to be accounted for in a relatively short period of time. They thought in terms of great earth "revolutions," "catastrophies" and "convulsions," to account for mountain building processes.



PLATE 3. Devil's Slide, five miles north of Gardiner, Montana. Southwest flank of Beartooth Uplift along the Gardiner thrust fault exposing near vertical beds of Paleozoic and Mesozoic age.
". . . there has been a terrible convulsion here in the past . . ." A. C. Peale, 1871 Hayden Report, Vol. 1, p. 174.

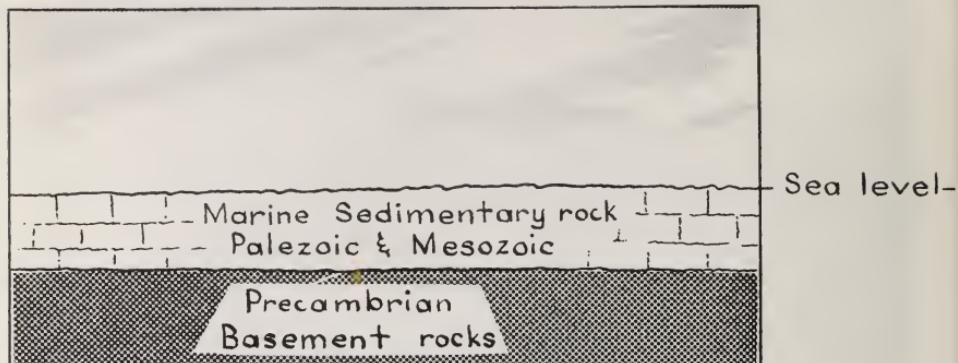
Modern day geologists favor the idea of more continuous deformation over extremely long periods of time.

Effects of this time of mountain building are most conspicuous in the Beartooth Mountains north and east of the park. Wilson (1934) has mapped the Gardiner thrust fault from its exposure near Devil's Slide to a point three miles east of Mt. Everts. He suggests that it may continue in a south-easterly direction as far as Cody, Wyoming, thus delineating the margin of a large thrust mass of rock constituting the Beartooth Mountains.

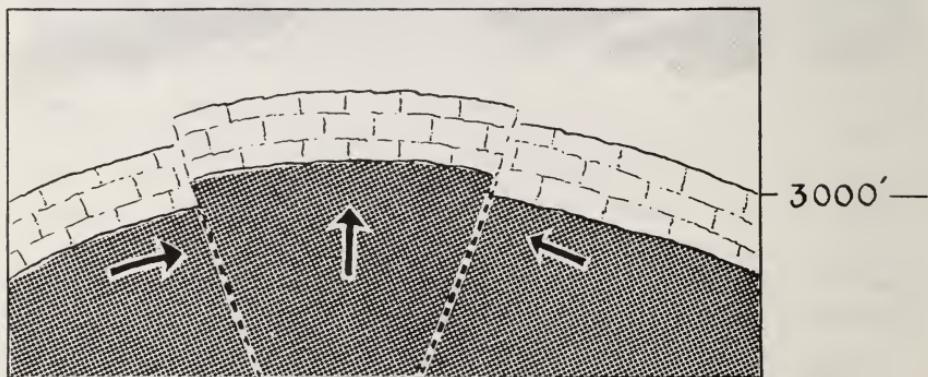
It is obviously impossible to know how high these first mountains stood, but very likely they were an impressive feature of the landscape but subject to the relentless attack of erosion, they were being worn down as uplift continued.

At Devil's Slide we can view the exposed remnants of one flank of this uplifted mountain block where erosion has performed the autopsy revealing structure that at one time was deeply buried.

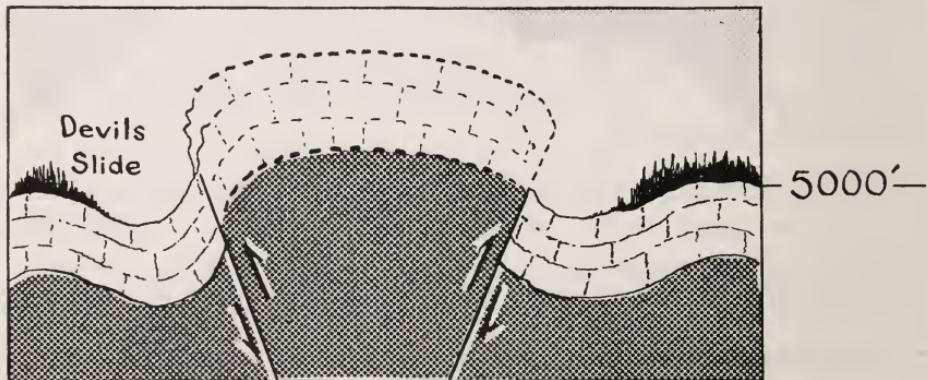
FIG. 4. Evolution of Beartooth Mountain Block as in illustration of Mountain Building Processes.



a) Late Cretaceous, before uplift.



b) Early Tertiary. Horizontal compression plus vertical uplift with beginning of faulting



c) After uplift and erosion. Devil's Slide is truncated limb of the uplift.

YELLOWSTONE'S FIERY PAST

A visitor confining his trip to the main loop roadway will encounter a diversity of rock types which surprisingly enough are almost identical in their chemical composition. In canyons and roadcuts extrusive volcanic products in the form of breccias, agglomerates, ash and welded tuffs are readily seen. In places these are interbedded with, or more commonly overlain by more quiet flows of rhyolite and basalt.

Beginning some 40 million years ago during the Tertiary period and extending up to the Glacial epoch this basin, hemmed in by mountain peaks, became the resting place for vast accumulations of volcanic products.

The earliest volcanic activity was of the explosive type and the observations of Dorf (1939) and Rouse (1937) indicate that beginning in the Eocene and extending into mid-Tertiary time these events happened; extrusion of andesite breccia, followed by basalts and an erosion interval with the whole sequence repeated a second time giving a maximum thickness to these deposits of 6,500 feet in the eastern part of the park. Outcrops of these rocks may be seen throughout the Absaroka Mountains and isolated remnants occur in the Gallatin to the northwest and in the Tetons to the south. Within the park the Washburn Range stands today as an island of breccia surrounded by the later plateau flows. The source of all this volcanic material and its mode of emplacement has been an enigma to geologists. Various features within the park such as Mt. Washburn, Mt. Sheridan, Electric Peak, and the "Crandall Volcano" on Hurricane Mesa east of the park have all been suggested as source areas. It seems likely that there were many sources and their locations may never be known. The crude stratification of the deposits is suggestive of emplacement as mud flows.

At times the volcanic fires subsided long enough for forests to grow and then these were buried under showers of ash, petrified, and the process repeated again and again. Today we can count the remains of 27 forests of petrified trees on the slopes of Specimen Ridge, proof of the rhythmic alternation between times of quiescence and explosive volcanic action. Man, accustomed to thinking in terms of his conventional time span of "three-score and ten," finds his imagination taxed to comprehend the time factor of the fossil forests alone. Yet when placed in their proper framework of geologic time, these events

are seen to represent but one grain of sand on the beach of time.

Explosive volcanic action gradually subsided and rivers and streams began their relentless task of dissecting the landscape. Gullies were deepened into valleys and these in turn became canyons. An erosion cycle was in progress but never carried through to completion because of renewed volcanic action of a different type; extrusion of the welded tuffs and rhyolite and basalt flows of the plateau.

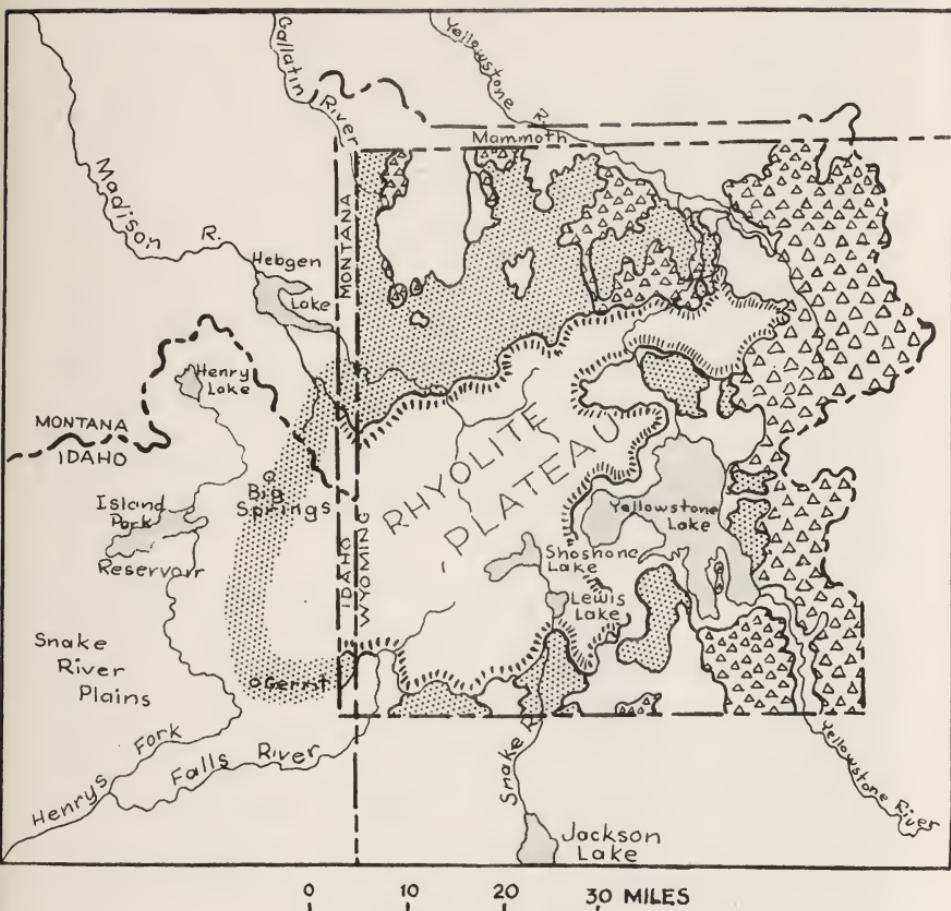
The first detailed study of the rhyolite plateau was undertaken by members of the U. S. Geological Survey in 1883. Results of their investigation appear in Folio No. 30 and in Part 2 of Monograph 32 of the U. S. Geological Survey. Considering the difficulties of travel and the hardships under which these men labored we can today only pay tribute to the prodigious amount of work they accomplished and the soundness of their basic geologic deductions. However, the earth sciences have made progress in recent decades and with refined mapping techniques and new tools of petrographic research it is apparent that the rhyolite plateau is much more complex than the earlier maps suggest.

F. R. Boyd (1957)¹ has made an outstanding contribution to the knowledge of Yellowstone geology. By careful field work and detailed petrographic studies he has shown that much of the "rhyolite" is in reality a welded tuff which he believes was erupted as incandescent tuff avalanches, emplaced in a rapid sequence of eruptions and deposited over the previous erosion surface. The present outcrop of these deposits encircles the Madison, Pitchstone, and Central Plateau covering an area of 1,000 square miles in Yellowstone and at least 1,000 square miles west and southwest of the park. Emplacement of the welded tuffs was followed by block faulting which depressed the central and southwestern part of the park creating a basin bordered in places by scarps up to 3,000 feet high. Faulting of the basin was followed by extrusion of flow after flow of rhyolite lava with minor amounts of basalt.

It is obviously difficult to assign geologic ages to extrusive volcanic rocks because the high temperatures destroy organic material and consequently the rocks are devoid of fossil material. The welded tuffs are believed to be Pliocene in age and some of the volcanism probably continued into Quaternary time.

¹ From thesis abstract by permission of F. R. Boyd.

YELLOWSTONE NATIONAL PARK AND VICINITY



EXPLANATION



—Margin of rhyolite
and basalt flows.



—Welded tuff



—Breccia

FIG. 5. Showing generalized outcrops of Tertiary extrusive volcanics. Unshaded areas within the park represent pre-and post-Tertiary outcrops. Based on work of F. R. Boyd (1957) and interpreted by the author.

By plotting the areal distribution of these volcanic products and estimating their thickness, Boyd concluded that the basin had been filled with 600 cubic miles of rhyolite and welded tuff, making Yellowstone one of the great volcanic areas of the world.

Geologists know that deep seated batholithic injections of granite have been recognized over most of the world and are commonly found to occupy the cores of folded mountain ranges. They are normally associated with areas of great crustal deformation. The Yellowstone region is notably deficient in granite and apparently has not been subjected to great deforming stresses since the early Tertiary. Almost fifty years ago Daly (1911, p. 63-67; 1933, p. 142-143) suggested that the rhyolite plateau is the founded crust of a roofless batholith. By comparing Boyd's (1957) petrographic analyses of the plateau rocks with similar associations from other parts of the world, Hamilton (1959) concludes that the Yellowstone plateau is more likely a collapse feature technically known as a lopolith.

The Geophysical Laboratory of the Carnegie Institute of Washington, D. C., has had a long standing interest in hydrothermal research in the park. In 1929 and 1930 they sponsored the drilling of two test holes, one near Old Faithful in the Upper Geyser Basin and a second in the Norris Geyser Basin. Fenner (1936) summarizes temperature and pressure data from these test holes and projections of an abnormally high thermal gradient of 20°C. per one hundred feet is suggestive of an igneous mass of unknown size existing at depths perhaps less than one mile below the surface.

Allen and Day (1935, p. 512) make a conservative estimate of a heat loss from the thermal areas equal to about 220,000 kilogram calories of heat per day. This requires a cooling and recrystallization of rocks below the surface of about one cubic kilometer every 50 years or some 200 cubic kilometers in the past 10,000 years.

What exciting food for speculation awaits today's Yellowstone visitor! To realize that he is viewing here a unique spot in the world where the magmatic hearths are yet warm and molten rock may exist less than a mile below the surface.

As one reconstructs the volcanic past it becomes easier to see why hot springs, geysers and earthquakes should be associated in Yellowstone.

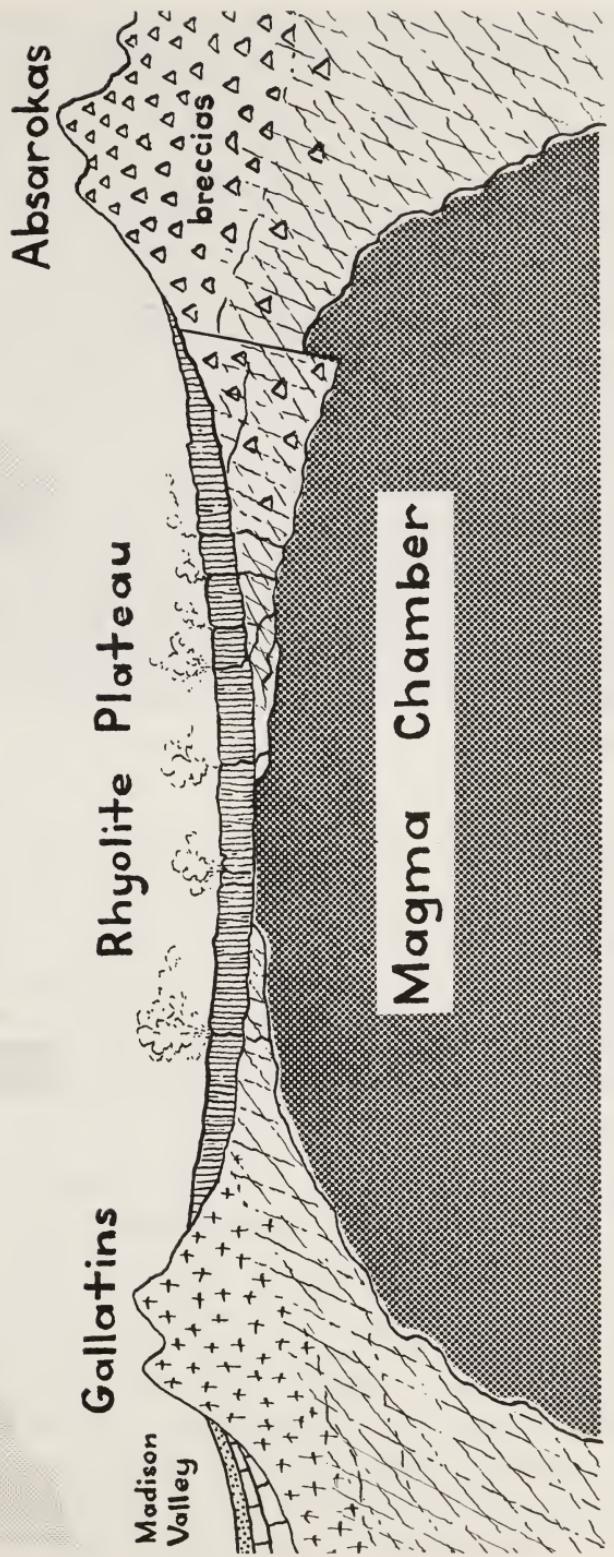


FIG. 6. Theoretical East-West Cross Section of Yellowstone Park Illustrating Faulting of Plateau and Intrusion of Lopolith.

THE MODERN PARK UNFOLDS

As the volcanic cover cooled, hydrothermal action with its consequent chemical alteration of the overlying rocks and the creation of early hot spring and geyser action took place. The stage was now set for the last decisive event, glaciation. Alpine glaciers, nourished by the snow fields of the surrounding mountains sent tongues of ice along pre-existing valleys, these lobes in places coalescing to create ice sheets that have scoured and planed off the topography. Occasionally hydrothermal action extended up through the ice to create interesting hills of tillite to be seen today in Twin Buttes and Porcupine Hills.

The final shaping of the Yellowstone landscape has been accomplished largely by water, both hot and cold. Streams fed by melting snow fields and rainfall begin their long tortuous journeys to both the Atlantic and Pacific dropping vertically over a mile and a half until sea level is reached. Streams, motivated by the force of gravity and laden with their cutting tools of sand and gravel have gashed the plateau with deep youthful V-shaped canyons.

Perhaps less impressive, but of equal importance, is the chemical work of hot waters. Ground water seeping through glacial gravels and fractured rhyolite, contacts the rising heat from the magmatic mass below. These hot waters are ever busy dissolving mineral matter at depth, transporting it upward in solution and then, after depositing some at the surface, the balance is carried on eventually to the oceans to add to their dissolved salt content. The Mammoth Hot Spring travertine terraces and the glaring white siliceous sinter deposits of the geyser basins have all been formed by this process. Great solution channels and cavities must honeycomb the underlying rocks rendering them highly susceptible to fracturing and collapse by earthquake tremors.

Allen and Day (1935, p. 129) made chemical analyses of these waters, estimated their rate of discharge, and concluded that 390 tons of mineral matter from the geyser basins are carried away in solution daily by streams in Yellowstone Park. Project this rate of solution into the geologic past and the conclusion seems warranted that the hot waters resources have played an important part in shaping the topography of the thermal areas.

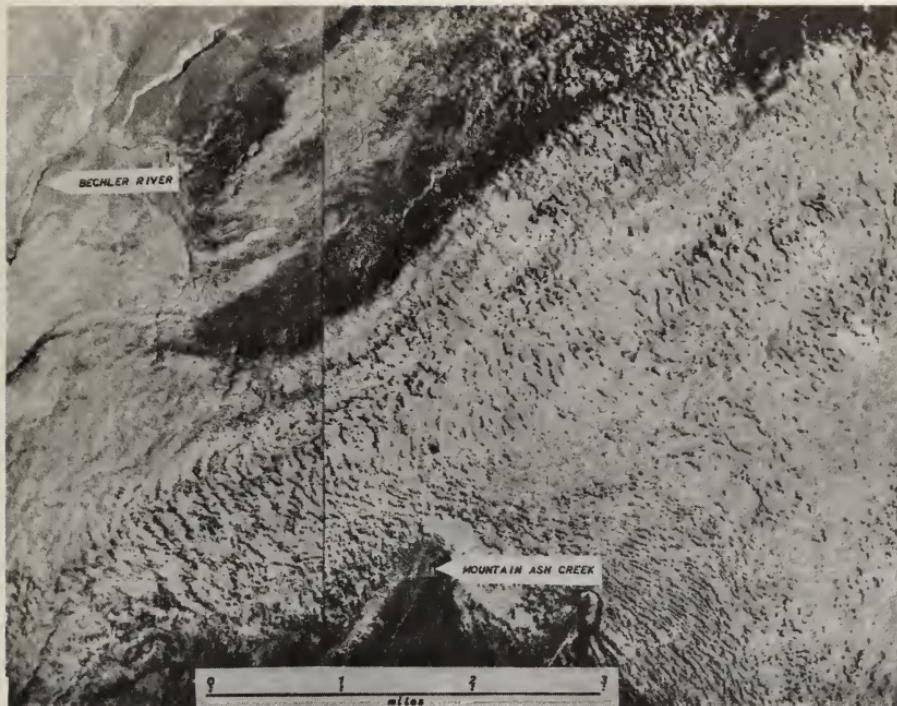


PLATE 4. Pitchstone Plateau lava flows southwestern corner Yellowstone Park. Park Aerial Survey photos 2-169 and 2-170.

A study of aerial photographs of the park permits interpretation of features that escape detection on the ground. Coniferous forests of lodgepole pine trees obscure the bedrock and mask the surficial features of the lava flows. Far in the interior of the Pitchstone Plateau there are rhyolite flows that appear as fresh as if formed yesterday. These flows seem to have moved like glaciers with great lobate swirls and flow lines accentuated by stands of timber.

Recent work done by the U. S. Geological Survey¹ has shown that a short distance west of the park, lava flows have been found on top of glacial deposits proving that volcanic action may have subsided no less than 10,000 years ago.

¹ Earthquake correspondence file, Yellowstone Park Library.

YELLOWSTONE'S STRUCTURAL FRAMEWORK

Important times of faulting (fig. 3) have been shown to occur with the early mountain building and later in the Tertiary after the emplacement of the welded tuffs. The more recent rhyolite flows are also severed by faults. This complex pattern of faulting is of extreme significance to both the geologist and the seismologist.

Pre-volcanic deformation has been largely obscured by the later flows of rhyolite and welded tuff. Consequently structural control in the underlying rocks can only be inferred in an indirect way by projecting structural trends from the surrounding area as they pass beneath the volcanic cover. Occasional mountain peaks within the park that stand above the flows permit a direct observation of folding and faulting.

One of the most exciting discoveries of the past year is the realization that post-glacial faulting has occurred in many places in the park. Love (1959, p. 1782) has found more than 50 faults on the Mirror Plateau where ice scoured valleys have been disrupted by displacements of 200 to 400 feet. He describes another area five miles west of Yellowstone's South Entrance where Beula, Hering and South Boundary Lakes were created by disruption of drainage along faults.

Plate 5 illustrates a spectacular interruption of a youthful drainage system north of Ice Lake and east of the Norris Geyser Basin. Here a series of valleys trending northeast-southwest have been intersected by a north-south trending normal fault that is downdropped to the east. The waters of Wolf Lake have been impounded against another smaller fault scarp that can be seen trending in a northwesterly direction.

Displacements in excess of 400 feet in the past 10,000 years can lead only to the conclusion that Yellowstone must have been one of the more active seismic areas in the United States and with this comes the realization that earth tremors must have played an important part in the evolution of the hot springs and geyser basins.



PLATE 5. Fault scarps on the Solfatara Plateau central Yellowstone Park.
Park Aerial Survey photos 1-144 and 1-145.

Prior to the 1959 earthquakes it was possible to observe some fracturing of the geyserite deposits in the thermal basins.



PLATE 6. Fractured geyserite in Potts Geyser Basin near West Thumb, Yellowstone Park. Note sinuous crack caused by an early unrecorded earthquake that has controlled alignment of thermal activity. Photo taken in August 1955 by W. A. Fischer.

Since the tremors of last summer extensive rifting of the geyserite cover can be seen in the Midway and Lower Geyser Basins.

Normal faulting of the plateau surface is probably caused by a foundering of the crustal cover or by adjustment of this rigid mass to the contracting magma below.

The position of known and suspected faults in the park is shown on Plate 36 (back of book).

EARTHQUAKE HISTORY OF IMMEDIATE AREA

F. V. Hayden, leader of the first scientific exploration party of the Yellowstone area, reported (1872, p. 82),

"While we were encamped on the northeast side of the lake, near Steamboat Point, on the night of the 20th of July (1871), we experienced several severe shocks of an earthquake, and these were felt by two other parties, fifteen or twenty-five miles distant, on different sides of the lake. We were informed by mountain men that these earthquake shocks are not uncommon, and at some seasons of the year very severe, and this fact is given by the Indians as the reason why they seldom or never visit that portion of the country. I have no doubt that if this part of the country should ever be settled and careful observations made, it will be found that earthquake shocks are of very common occurrence."

A. C. Peale, mineralogist and member of the Hayden expedition has recorded the following in the same volume, (p. 189-190):

"On the 19th of August we moved our camp down the Lake to Steamy Point . . . Our camp was situated on a high bluff on the edge of the lake . . . Every night while at this place we experienced earthquake shocks, each lasting from five to twenty seconds. We named it Earthquake Camp."

This earliest record of seismic activity in the park was also noted by Captain J. W. Barlow, leader of a second scientific expedition encamped on the southeast arm of Yellowstone Lake. Barlow's report (1872, p. 38-39) contains the following entries:

August 20, 1871—"We experienced last night the singular sensation of an earthquake. There were two shocks, the first one being quite severe accompanied by a rumbling and rushing sound."

On the 21st of August, Barlow had joined the Hayden camp at Steamboat Point and notes once again (op. cit., p. 39),

". . . frequent earthquake shocks were felt by the party while at this camp."

Apparently the tremors had been impressive enough to cause Barlow to comment once again on the 22nd of August, (op. cit., p. 39) where he was encamped near the Lower Falls of Yellowstone River,

"During the night the concussion caused by the falling water reminded me of the earthquakes felt on the lakes a few nights previous."

In the years since the Hayden Survey the adjoining states have been subjected to many earthquakes.

TABLE 1.

Stronger Earthquakes in Surrounding Area

Year	Date	Time	Locality	N. Lat.	W. Long.	Area M.M.	Inten- sity M.M.
1915	May 8	9:10	Wyoming	44.9°	110.7	10,000	5
1925	June 27	18:21	Montana	46.2°	111.2	310,000	8
1935	Oct. 18	21:48	Helena, Mont.	46.6°	112.0	230,000	8
1947	Nov. 23	2:46	S. W. Mont.	44.8°	112.0	150,000	8
1959	Aug. 17	11:37:15	S. W. Mont.	44° 50'	111° 05'	500,000	not yet determined, probably 10

Authority: Earthquake History of the United States, U.S.C.G.S., 1958 ed.

It seems that on an average of about once every ten years a strong earthquake is registered in the adjoining states.

Yellowstone has had its share of tremors. Table 2 presents a summary of available data but should not be considered as all inclusive because of a number of factors: Reporting of earthquakes was done haphazardly for many years and much of the park is primitive wilderness area untouched by man and seen only rarely during the summer months. With the approach of winter the park is gradually closed and only a few outpost stations are manned throughout the year. Many tremors must have passed un-noticed in this great wilderness area. To quote the words of Dr. Stephen W. Nile, Collaborator in Seismology for the U.S. Coast Geodetic Survey at Butte, Montana, "If only the Moose and Elk could talk!"

The frequency, intensity, and epicenters* of known earthquakes in the Yellowstone area have been recorded on Plate 36 (back of book) and in Table 2. Certain inferences seem apparent. The South Entrance, Yellowstone Lake, Old Faithful, and Mammoth appear to have been the most active areas prior to 1959.

The 1959 main shock and aftershocks have centered largely in the northwestern corner of the park around the Gallatin Mountain Range. The one most active aftershock epicenter has been at 45° N. Latitude and 111° W. Longitude.

* Note. The accuracy of epicenter determinations is dependent upon the number and quality of the seismograms. For example, an epicenter determined at 45½° N. Lat. is less accurate than one determined at 45° 30' but both are plotted on the map in the same place.

TABLE 2 SEISMIC HISTORY OF YELLOWSTONE NATIONAL PARK

Year	Date	Time	Area Affected	Epicenter N. Latitude	W. Longitude	Magnitude Modified Mercalli	Intensity Weske Fall - Remarks	Author
1871	19 Aug						Steamboat Point and Southeast Arm of Lake Yellowstone	(1) Vol II, p 121
	8 May	9 10	10,000 sq mi	44° 9'	110° 7'	V	North-central part of Yellowstone Park	(4) Vol II, p 141
1915		4 55					Three distinct shocks at Canyon & Tower Falls, One at Mammoth, no damage done	(5) Vol II, p 151
	27 June	6 22 7 05 8 39					Felt throughout the park Building damage at Gardiner Montana	(3) (9) Vol II, p 5
1925	6 Dec	16 16				II	Felt by several	(4) Serial # 424
1926	31 July	23:26				IV	Lake Ranger Station Felt by many Windows rattled Pictures disarranged Dishes and groceries disturbed, surface sounds	(4) 1926 ed
	24 Aug	19 40		44° 5'	110° 5'		Light shock with a number of aftershocks Dishes thrown down, lights swung	
	25 Aug	7 45					Shook south end of Lewis Lake, water disturbed	
	28 Aug	4 00		44° 4'	110° 8'	IV	Snake River Ranger Station, rattling of doors and windows, many awakened	
1930		7 40					Shock disturbed water in Lewis River to Snake River Ranger Station Three shocks	(4) 1930 ed
	27 Aug	17 00					North end of Yellowstone Park Light	
	31 Aug	23 45				V	Norris Junction Light	
	15 Sept	20 10					Snake River Ranger Station Light	
	25 Sept	4 00					Snake River Ranger Station Rapid rocking, west to east, felt by all Subterranean and surface sounds heard	
	22 Dec	9 15		44° 4'	110° 8'			
	24 Aug						South Entrance 18 aftershocks Roads rattling of camp equipment Building shook repeatedly Dishes thrown	(5)
1931	25 Aug	7 45					South end of Lewis Lake in am - turbulent Moderate	
	26 Aug	4 00					South end of Lewis Lake Felt also at South Gate Everyone aroused	(4) Serial # 553
	27 Aug						South end of Lewis Lake Three small shock in 24 hours	(6)
1933	5 June	4 15					West Yellowstone Montana Slight rocks awakened few	(4) Serial # 579
1934	13 March	2 13				IV	Pendulum clocks stopped all objects moved Mammoth*	(4) Serial # 593
1935	18 Oct	21 48	230,000 sq mi	46° 37'	111° 58'	VIII at Helena, Montana	Yellowstone National Park Felt by many, frightened few	(9) Vol XII, p 52
	14 Jan	21 40	1,200 sq mi	44°	110° 5'	V later raised to VI	Lake Hotel Cracked plaster, loose swinging doors would not close South entrance cracked two brick chimneys for several feet and moved small objects Rocked beds at Moran, Wyo Not felt at Jackson, Wyo	(9) Vol XIII, p 8 (4) Serial # 610
1936	24 June	8 47					Old Faithful Felt indoors	(9) Vol XIII, p 43
	7 Sept	16 30					Weak shock at West Yellowstone Motion and at Mammoth Hot Spring Wyo	(4) Serial # 610
	27 April	15 34					Slight shock felt only by those in vicinity of Old Faithful Hotel	
	7 Aug	0 30 about					Ranger at Mt. Sheridan awakened Wall maps and lamps swayed	(4)
1937	8 Sept	16 30					West Yellowstone, Mont. Slight Also felt at Mammoth	Serial # 619
	15 Sept	21 27					Lake Ranger Station Awakened many Other shakes felt during the night Felt by a few at West Yellowstone Montana, at 21 45	
1939	22 Oct	18 40					Lake Ranger Station Sharp shock generally felt No damage	(4) Serial # 637
1940	24 May	4 50, 5 10, 5 25, 8 55					Moderate shocks felt mostly all in Old Faithful Area	(4) Serial # 647
	1 May	4 50					Canyon Dishes rattled, light bulbs swung, pictures displaced	(10)
	5 Aug	15 34				V	West Thumb Felt by all Rattled windows and dishes	(4) Serial # 682
1942	25 Sept	8 50				IV	Lake Ranger Station Felt by all in community	
	31 Oct	9 40					Old Faithful Shook Ranger Station for three seconds	(10)
	1 Nov	9 10 & 9 45					Snake River Ranger Station Felt by thirty people	(4) Serial # 662
		9 40					Old Faithful and Snake River Felt by all in area Rattled windows	
1943	3 Feb	5 15 9 30				IV	Old Faithful All awakened Houses creaked windows rattled Six different quakes between 05 15 and 09 30 a.m. Severest was at 09 15 a.m.	(6)
	25 Oct	14 25					South Entrance Three distinct tremors felt, first at 08 27 p.m. Was weak, the second immediately following was strong enough to rattle dishes and swing suspended objects in a SE direction, the third at 08 36 p.m. was slight. Thus persons at station in two separate buildings felt these shocks. The first at 08 27 p.m. appeared slow followed immediately by a rapid shaking of the building. The first two shocks were felt by several persons at the Flagg Ranch two miles south of this station. The third shock was felt by at least three persons at the Flagg Ranch. Frightened all at the Station At Moran it was felt with abrupt and E-W swaying. Dislodged canned goods Subterranean sounds were heard by several Hanging objects swung Building swayed slightly Shock was reported to have been from 14 miles west and also 12 miles east of Moran	
	21 April	18 32					Canyon Felt by two Hanging lights swing	
1945	23 April	11 31					Canyon and Yellowstone Lake, felt by several, by some outdoors Houses creaked Trees and bushes slightly shaken Overturned vases and small objects No damage to buildings	(4) Serial # 699
		14 24 14 58 15 13					Lake Station Lake Hotel Motion rapid, lasting a few seconds Felt by observer in lake area Houses creaked Overturned vases and small objects	
	24 April	9 20					Yellowstone Lake Motion rapid, lasting two seconds Felt by two Houses creaked, overturned small objects Dull sounds preceded each shock	
	8 Jan	12 37				V	Yellowstone Park Motion rapid, lasting about two seconds Felt by low Rattled windows, overturned vases and small objects After shocks occurred at 14 46, 15 37, 15 33, 16 16 and 22 25 All were preceded by a moaning sound	
	31 Oct	18 23					South central section of Yellowstone Park Building of Snake River Ranger Station trembled Windows rattled and small objects were disturbed Pictures swung on walls Slight rumble heard inside house immediately after and during shock	
1947							Southwest Montana, Hebgen Dam and West Yellowstone, Montana	
	23 Nov	02 46 05	150,000 sq mi	44° 47'	112° 02'	to X	Southwestern Montana Yellowstone Park Motion rapid, lasted about one minute Felt by all Awakened all frightened many Wind & rain has rattled houses creaked Hanging objects swung and pendulum clocks facing North stopped Old time residents state this was the most severe shock ever felt in Yellowstone Park Several were frightened at Snake River Station Beds rattled Two shocks were felt in northeast corner of Park Buildings creaked and loose objects rattled Gasoline lamps hanging on hooks from ceiling swayed E-W	(4) Serial # 730
1948	19 July	17 00					East Entrance Light shock felt by several Rattled lights, hanging objects swung Shifted small objects on stove	(4) Serial # 746
	9 Nov	16 23					Old Faithful Slight shock felt by all at ranger station Building creaked	
	10 Nov	00 47					Old Faithful Light shock felt by all at ranger station Awakened all in home	

FOURTH FLOOR

Before attempting to explain why earthquakes occur here it would be best to examine the position of the park in terms of the seismic pattern of the United States. Figure 1 plots the distribution of earthquakes in the United States through 1957. Of particular interest is the belt of earthquakes that follows the Rocky Mountain zone of overthrust faults in Montana and then shifts westward in Utah to follow the Wasatch Mountain front southward into Arizona. This is a major zone of weakness in the earth's crust that has been responding to the accumulation of stresses throughout recorded human history.

Watching the shifting pattern of epicenters during 1959 (Plate 36) seems suggestive of block faulting, with a shift on one block putting a neighboring block out of gravitational balance. Continued adjustments have taken place with several thousand aftershocks being recorded in the months following the initial displacement.

EARTHQUAKE WATER TABLE EFFECTS AROUND THE WORLD

The alluvial mantle that veneers bedrock over most of the earth is the realm of ground water, one of our most precious natural resources that serves to feed water wells and permanent flowing streams. The United States Coast and Geodetic Survey, Ground Water Branch maintains observation wells with automatic recording gauges at many points in the United States.

The August 17th, 1959, earthquake caused a change in water level in 177 wells in 25 states and Puerto Rico. Minor fluctuations were recorded as far away as the Hawaiian Islands and a maximum change of ten feet was noted in an artesian well 85 miles south of Hebgen Dam. A mine water pool in the Northern Anthracite field near Wilkes Barre, Pennsylvania, was also observed to fluctuate.

Table 3.* Summary of Effects of Montana Earthquake on Water Levels in Observation Wells

State	Number of Wells	Maximum Fluctuation (ft.)
Alabama	20	1.3
Arizona	3	.29
Arkansas	6	.06
California	22	1.11
Colorado	1	.03
Florida	15	.48
Hawaii	4	.10
Idaho	18	10.0
Illinois	4	.95
Indiana	10	.49
Kentucky	2	.28
Michigan	5	.26
Minnesota	6	.67
Montana	10	1.76
Nebraska	1	.23
Nevada	3	1.00
New Jersey	6	1.42
New Mexico	10	1.3
New York	2	.28
Ohio	7	.24
Oklahoma	1	.28
Puerto Rico	1	.01
Texas	4	.60
Utah	5	5.1
Washington	6	1.15
Wisconsin	5	1.00

* Water Resources Review, U.S. Geological Survey—Sept. 1959.

Earthquake waves shaking the unconsolidated sand and gravel cover cause a compaction of the material. This reduces the available pore space and drives water out of the voids thus causing increased discharge. During the period August 1-16 the net inflow into Hebgen Lake was about 600 cubic feet per second. From August 21-31 the inflow increased to about 1,100 cubic feet. It is impossible to predict what long range effect this increased discharge may have on water wells in the immediate earthquake area.

Locally a number of sinuous fissures were opened in the alluvial cover and ground water and sand were forcibly ejected from them. Such features are known as sand spouts. Near Hebgen Lake Lodge a fissure 50 feet long, 20 feet wide, and about 9 feet deep ejected water, sand and cobblestones. In Yellowstone Park smaller sand spouts have been observed in the Madison Junction campground and also two miles east near the base of Tuff Cliff.

Effects of the earthquakes on Yellowstone's hot water resources are discussed in the chapter "Changing Geysers and Hot Springs."

A TOUR OF THE EARTHQUAKE AREA

Effects of the 1959 earthquake can best be followed by reference to Plate 37 (back of book) where numbered sites are described in numerical sequence.

SITE 1.

The Madison River at this point has carved a deep gorge through the heart of the Madison Range. Steeply inclined metamorphic rocks of Precambrian age dip to the north. Prior to the earthquake a buttress of dolomite precariously supported a mountainside of deeply weathered schist and gneiss. Conditions were favorable for landslides to occur.

It is believed that earthquake vibrations shattered the dolomite buttress, the mountainside came down in one roaring mass, rose 400 feet vertically up the north wall and came to final rest in the canyon. The rapid emplacement of this 80 million tons of rock in the narrow confines of the canyon sent an air blast of cyclonic proportions that added to the fury of nature on a rampage.

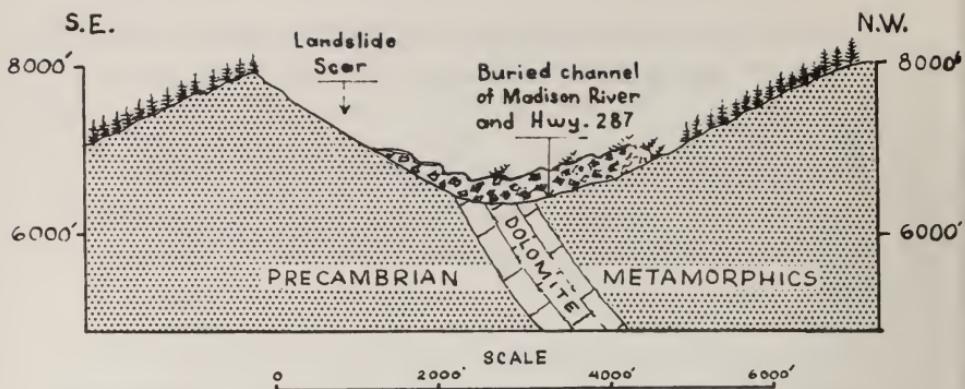


FIG. 7. Geological Cross Section Through Madison Canyon Slide Viewed Down-Canyon From Site 1. Adapted from Witkind (1959).

SITE 2.

The landslide which dammed the Madison River created "Earthquake Lake" between the slide and Hebgen Dam.



PLATE 7. The Madison Canyon slide dammed the Madison River to create "Earthquake Lake." Sleeping bags and supplies abandoned by refugees. Photo by William B. Hall, 21 Aug. 1959.

SITE 3.

Hebgen Lake Dam, an earthfill structure with a concrete core wall, built in 1913 by the Montana Power Company, was cracked in several places and inundated four times by a wall of water set in motion by the agitation of the lake basin. Lake oscillations of this type are known as seiches.



PLATE 8. Hebgen Lake Dam, aerial view. Note erosion of downstream face of dam caused by seiches. New fault scarps appear as white ribbons on left hillside. U. S. Forest Service photo.

SITE 4.

Old faults were reactivated along the north side of the lake, portions of the lake shore slumped, and the whole lake basin was tilted so that the north side depressed and the south side was elevated.



PLATE 9. Hebgen Fault, north shore of Hebgen Lake. Vertical displacements up to 20 feet have been measured on these new fault scarps. Slip out in foreground severed main road and a bypass was constructed. U. S. Forest Service photo.

At the Duck Creek Wye, Highway 191 was offset by a fault and a family fleeing from the scene of devastation ran from one peril into another. Fortunately none were injured when their car overturned.



PLATE 10. Overturned automobile at Duck Creek Wye on Highway 191. Photo by William B. Hall, 18 Aug. 1959.

With repeated aftershocks it seemed wise to curtail travel and signs like this were erected.



PLATE 11. U. S. Forest Service earthquake sign, West Fork of Madison River. Photo by Dorothy P. Nile, 18 Oct. 1959.

SITE 5.

West District Ranger Elliot Davis¹ found himself in the center of activity,

"About 11:40 p.m. on the night of August 17, 1959, I was lying in bed reading, when suddenly the room began to move and heave and an unearthly roar filled the air. My wife was asleep, but the noise brought her to her feet and we made our way the length of the house to the door. The Park home in which we live has only one door, in the front; as we sleep in the back, it meant walking the length of the hall, holding onto the walls to keep from being thrown down, while china, crockery, canned goods and books cascaded from the cabinets and bookcases, adding to the confusion."

All rangers and men in the area reported for duty at once, buildings in the government area were inspected, the fire truck was started in anticipation of fire and a quick tour of the town of West Yellowstone was made.

The West Entrance to Yellowstone Park was immediately closed to incoming traffic while a procession of cars began to wend its way from Madison Junction toward the gate. Campers roused from their sleep hastily stuffed their belongings into cars and were slowly working a route around rockslides and through the dust filled air of the Madison Canyon.

SITE 6.

The north and south walls of the Madison Canyon were severely shaken by earth tremors and great blocks of rock shattered from the canyon rim, cut swathes through the timber as they cascaded down to the roadway below. Boulders the size of an automobile bounded by leaps and jumps, some ending up in the Madison River to nestle among lichen-covered rocks of comparable size brought down by a similar event in the not too distant past.

Choking clouds of pulverized volcanic ash dust filled the air.

¹ "Experiences at West Yellowstone on Night of Earthquake, August 17, 1959"—West District Ranger Elliot Davis, Yellowstone Library Earthquake File.



PLATE 12. Large rock on road to West Yellowstone one and one-fourth miles east of Mt. Jackson slide. National Park Service photo (59-955)



PLATE 13. Rockslide on shoulder of Mt. Jackson. National Park Service photo (59-792).

One more chapter had been written in a process that has been going on here for millions of years.

A few days after the earthquake I climbed through these slides to the summit of Mt. Jackson searching for rifting of the cliff face that might create a danger in opening the road below. None was found and to my total amazement there was no evidence of movement back of the cliff, not a pine needle disturbed or a log rolled over!

The Madison Canyon has been established along the contact of a plateau flow with a fault scarp. A normal fault, upthrown on the north side, has been mapped (Plate 36) from near the base of Mt. Jackson in an easterly direction through Madison Junction following the Gibbon River and Canyon Creek, thence north to die out in the Gibbon Meadows. The bold south face of Mt. Jackson and Purple Mountain have been eroded out of welded tuff on the fault scarp. South of the Madison River, Mt. Haynes and National Park Mountain are the front of a rhyolite plateau flow and the welded tuffs underlie them but are not exposed as this is the downthrown side of the fault.

A branch fault cuts through Secret Valley to create a downdropped block or graben.

The Secret Valley, Madison Canyon, and Gibbon Falls area, because of their fault control and proximity to the epicenter, show some of the greatest earthquake effects.

SITE 7.

A short distance east of Madison Junction the road passes near Tuff Cliff where a hillside was shattered by the earthquake and trees were knocked over by the rockslide.

When movement occurs along a fault the wall rock is smoothed, polished and grooved in a direction parallel to the displacement. Rocks grooved in this manner are said to be slickensided. At the base of Tuff Cliff there are slickensided boulders of tuff broken from an old fault surface (Plate 36) by the 1959 earthquake. The apparent freshness of the striations on a rock as soft as tuff is proof of comparatively recent movement. However, limited observations to date reveal no evidence of renewed faulting in this locality during the 1959 earthquakes.



PLATE 14. Rockslide at Tuff Cliff. National Park Service photo (59-961)

On the 30th of September 1959, Park Naturalists Mebane and Frisbee visited Secret Valley and found a large mudflow had occurred in the northwest corner of the valley which had moved downslope with sufficient force to uproot trees and create large log jams.



PLATE 15. Mudflow in Secret Valley with uprooted trees. National Park Service Photo (59-1257)



PLATE 16. Mud plastered trees in Secret Valley one-half mile from source area. National Park Service photo (59-1256)

SITE 8.

The route of the Gibbon River from Gibbon Meadows to its confluence with the Firehole River at Madison Junction is essentially fault controlled throughout its course. Gibbon Falls is critically situated in the downfaulted block known as Secret Valley. Shock waves from the August 17 earthquake seem to have channeled their energy in this area causing new thermal activity and extensive road damage by rockslides and fracturing of the road cover.



PLATE 17. Retaining wall separation at Gibbon Falls. National Park Service photo (59-1084)



PLATE 18. Rockslide at Gibbon Falls. National Park Service photo (59-1090)

The Firehole River, fed by Madison Lake, follows a north-easterly course through the Upper, Midway and Lower Geyser Basins. Tributary streams and discharge from the thermal areas increase its volume downstream.

As the river leaves the lower Geyser Basin it has dissected its canyon through zones of weakness in one of the rhyolite plateau flows. At Firehole Falls the canyon wall rock consists of poorly lithified masses of perlitic rhyolite and obsidian. Earth tremors shattered this material and the ensuing rockslide completely buried the road.

There is no evidence for fault control at this point and the slides apparently were caused by the nature of the rock and its inability to withstand the vibrations.

Fortunately the old Mesa Road was undamaged and this provided a route of travel around the slide area and permitted people to vacate the Madison Junction campground.



PLATE 19. Rockslide in Firehole Canyon. National Park Service photo (59-930)

SITE 10.

The Twin Buttes in the southwest corner of the Lower Geyser Basin, are hills of glacial drift cemented by siliceous sinter from pre-glacial hot spring and geyser action. Fumaroles are still active on both hills.

Park Rangers Frisbee and Mebane visited this area on September 25, October 14, and November 19, 1959, and reported the presence of large steaming cracks on both buttes which they believed to be the result of massive slumping initiated by the earthquake.

Study of Mebane and Frisbee's tape and compass map of the fractures reveals several large fissures with depths of six to fifteen feet and smaller ones with lengths up to 350 feet. Many of these are now active fumaroles.

Rifting of Twin Buttes would be expected because with every earthquake the damage is greatest in poorly consolidated alluvial deposits.



PLATE 20. Large fissure on face of south Twin Butte, looking east across Midway Geyser Basin. National Park Service photo (59-1252)



PLATE 21. Small fissure and fumarole on north Twin Butte. National Park Service photo (59-1254)

SITE 11.

Visitors in the Old Faithful area were jolted by the shocks with the Inn bearing the brunt of the damage. At 1:43 A.M. the chimney over the Inn dining hall collapsed and fell through the roof.

A sprinkler system was activated in one wing, other chimneys were damaged and the danger of falling brick led to the evacuation of the building.



PLATE 22. Chimney damage on Old Faithful Inn. Note offset of bricks near center of chimney caused by earthquake. Yellowstone Park Company photo.

Visitors in the west wing were allowed to reoccupy their rooms, however few chose to do so. At 7:30 A.M. a barricade on the Old Faithful-West Thumb road was removed and people were advised by public address system that they could leave the park by all entrances except the West.

SITE 12.

From Canyon to Norris Junction the road follows a course through dense stands of lodgepole pine on the Solfatara Plateau. At Virginia Cascades on the Gibbon River the road becomes a shelf road with log cribbing for support and it has been cut back into a jointed exposure of rhyolite. Small rockslides took place here and the road was closed to public travel by an order of the Superintendent.

Minor damage was recorded at Norris. A chimney fell in on the old Soldier Station and some glass broke in the museum.

SITE 13.

Immediately after the earthquake it became apparent that a great many streams and lakes were muddied up as a result of jarring of the ground water table. Compaction of alluvial material results in a reduction in pore space and the water drives out the finer sedimentary particles. In some areas mud slides added to the problem.

Most of the drainage on the west side of the park was murky and Grizzly Lake and Straight Creek were exceptionally turbid.

This condition persisted and one month after the earthquake Park Naturalists Germeraad and Mebane found Grizzly Lake still uniformly muddy and cold.

Springs flowing into the lake from the west shore were clear and cold, but Straight Creek flowing into it from the south, was even muddier than the lake.



PLATE 23. Turbid water of Grizzly Lake one month after earthquake.
National Park Service photo (59-1247)



PLATE 24. Junction of Straight Creek and an un-named creek showing mixture of clear and turbid waters one month after earthquake.
National Park Service photo (59-1248)

SITE 14.

Golden Gate Bridge of cantilever construction was completed by the National Park Service in 1934. The road at this point has been cut back into exposures of welded tuff that are crudely jointed.



PLATE 25. Rockslide after scaling operations at Golden Gate south of Mammoth. Road crews were faced with cleanup jobs such as this after the tremors subsided and it was considered safe to open roads to public travel. National Park Service photo (59-980)

Earthquake tremors shattered blocks of tuff and a rockslide descended onto the bridge and covered the road. Fortunately once again a back road was undamaged and travel from Norris to Mammoth was possible by way of the Bunsen Peak road.

SITE 15.

Mammoth Hot Springs is headquarters for Yellowstone National Park. Here Mr. Lemuel A. Garrison, Park Superintendent, and his staff direct the activities essential to the operation of the oldest and largest of our national parks.

The community of Mammoth was rocked by the initial shock with damage to buildings caused largely by falling chimneys. Road crews set out at once to check the status of a rockslide that has been slowly encroaching on the north entrance road four miles below Mammoth. This slide had not moved but a new one had developed at Golden Gate creating a road block.

Startled residents gathered in small groups and were able to see rockslides cascade from the summit of Mt. Everts, the dust creating an eerie effect in the moonlight. Mt. Everts consists of stratified Cretaceous rocks that are unconformably overlain by welded tuff. Shaking of the Mt. Everts fault block resulted in rock fall from the cap.

The community was jolted by aftershocks for days afterward and as a safety precaution some buildings were temporarily abandoned, board enclosures were erected for protection against falling stone and the Superintendent moved his headquarters into a tent.



PLATE 26. Temporary walkway shelter erected at Mammoth Museum to protect personnel from falling rock. National Park Service photo (59-1134)



PLATE 27. Emergency Superintendent's Office at Mammoth. From left to right M. D. Beal, F. Sylvester, H. Child, Supt. L. A. Garrison, J. Nichols, Asst. Supt. L. Gastellum, G. Helppie, J. Haynes, J. Joffe and T. Hyde. National Park Service photo (59-734)

SITE 16.

Yellowstone River departs from Yellowstone Lake at Fishing Bridge and commences a leisurely journey across the Hayden Valley. Gradually the river changes from a placid body of water to a seething torrent as it picks up speed to descend in a foaming cascade over the Upper and Lower Falls. Here in all its pristine beauty is the Grand Canyon of the Yellowstone.

The canyon has been dissected through rhyolite flows that have been intensely altered by an earlier period of geyser and hot spring action. Rock decomposition in every stage from slightly altered rhyolite to pure kaolin can be seen throughout the colorful portion of the canyon.

Conditions here are favorable for rockslides. Clouds of dust were observed at a few localities in the vicinity of Artist's Point but close inspection reveals little if any damage. Increased distance from the epicenter probably saved the canyon from destruction.

However, an aftershock of early September did cause some rock to tumble down on Uncle Tom's trail necessitating its closure for public safety.

CHANGING GEYSERS AND HOT SPRINGS

The association of geysers, hot springs, mud pots and fumaroles is believed to represent a declining phase of volcanic activity. Steam and other gases rising through fractures from the magmatic source at depth come in contact with cold descending ground water. Convection current circulation of the water permits hot springs to attain various temperatures depending on the ease and freedom of circulation. Where circulation is impeded by a twisting tube underground, the water cannot heat uniformly and as steam pockets form they expand and lift the overlying column of water into the air to create an eruptive hot spring technically known as a geyser. A sedimentary deposit of siliceous sinter or geyserite is precipitated within the plumbing systems of the springs and also around their orifices. The source of the silica is the rhyolite lava flows that underlie the basins. Where there is a deficiency of ground water the wall rock is commonly intensely altered causing rhyolite to break down into clay and with the oxidation of iron compounds there are developed colorful features known as paint pots. Fumaroles are fractures that convey steam from below.

To date we have no confirmatory evidence that the geyser basins are fault controlled. Many of the smaller thermal areas are localized along the margins of lava flows. The larger basins may be depressions where hydrothermally altered rock has been easily removed by later erosion. The basins are now paved with a cover of glacial gravel that serves as the porous aquifer to feed the thousands of hot springs and geysers.

During the hours immediately following the main earthquake shock the chief concern was for the safety of the people; few had time to consider what might be happening in the geyser basins. Had the earthquake occurred during daylight one could probably have seen more geysers and hot springs in action than at any time since the establishment of the park.

On the morning of August 18, Park Naturalist George D. Marler made a reconnaissance of the Upper, Midway and Lower Basins. A rapid inventory revealed that 298 geysers and hot springs had erupted and of this total 160 had no previous record of eruptive activity. Some of the less accessible thermal areas showed signs of increased activity and some geysers

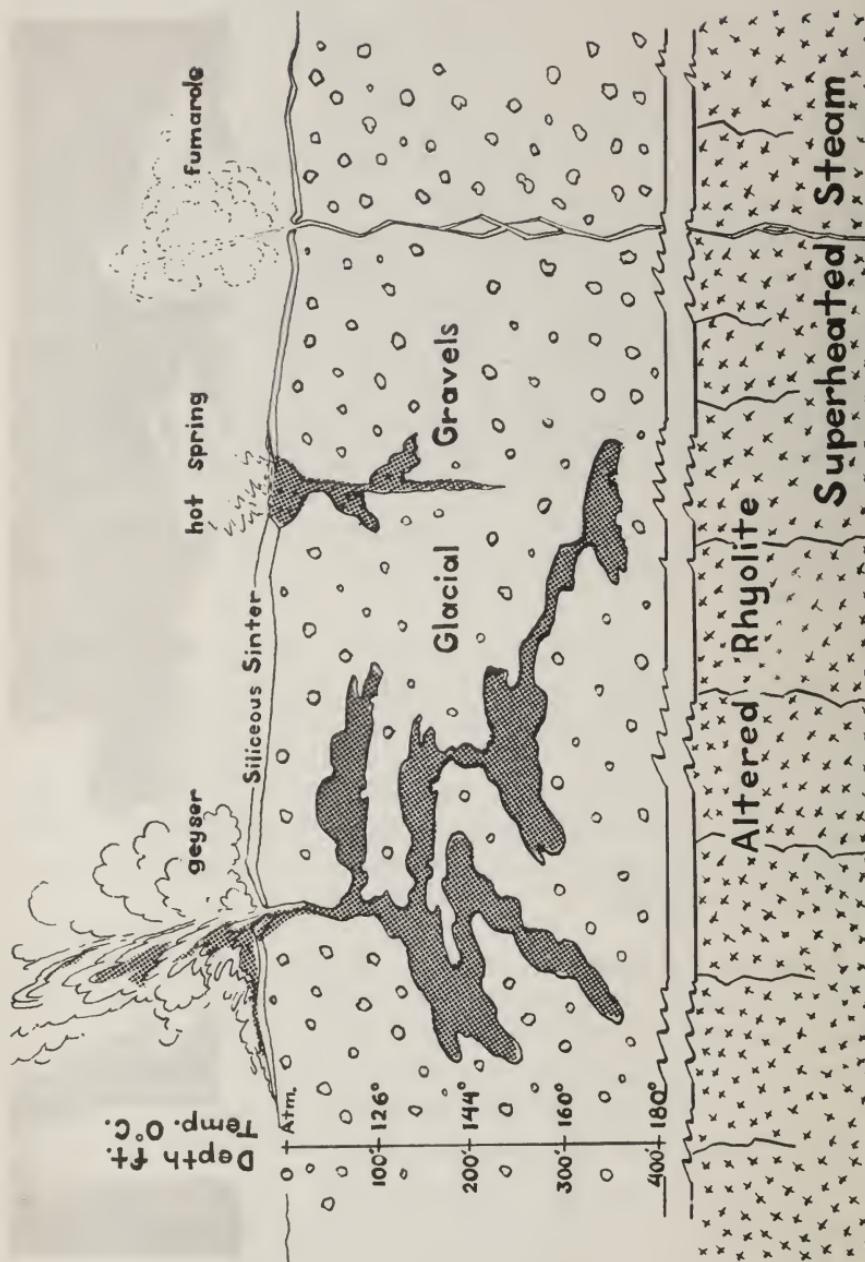


FIG.

8. Cross Section of View of a Typical Geyser Basin. Depth and temperature data based on Fenn (1936).

dormant for years were rejuvenated. There was an obvious need for a thorough inventory of Yellowstone's thermal features.



PLATE 28. Sylvan Springs showing increased thermal activity after the earthquake. National Park Service photo (59-1090)

The National Park Service approved a project known as the "Emergency Interpretive Study of Earthquake Phenomena, Yellowstone National Park," and under the guidance of Chief Park Naturalist Robert N. McIntyre, Park Naturalists began the laborious accumulation of data on temperature, discharge and physical change.

Temperatures were recorded by Taylor Maximum Registering Fahrenheit Thermometers and discharge was computed by using a large caliber hose and graduated pail to determine the flow in gallons per minute. The criteria of physical change included: 1) evidence of unusual eruptions, such as broken and dislocated sinter rims, eroded soil nearby, dead or dying vegetation adjacent to the feature, and increased erosion of the drainage channels; 2) a large rise or fall in temperature compared with recent records; 3) a change in water level as

evidenced by flooded margins or dried out algae above present water level; and 4) recent cracks through sinter or soil in the immediate area. All major features were documented by photographs permitting a comparison of the 1959 status with that of earlier years. The study required pack trips into remote areas and with early snows and sub-zero weather, working conditions were at times hazardous.

From these observations there has resulted a vast accumulation of data that are now being evaluated. A few of the more pronounced changes believed to be of interest to park visitors are summarized in the pages to follow.

Yellowstone's major thermal resources are concentrated on the western side of the park along the Firehole and Gibbon River drainage. Smaller areas are found at Shoshone Lake, Heart Lake, West Thumb, Hayden Valley and other remote areas seldom seen by man.

Observations to date show that the greatest physical changes occurred on the west side, particularly in the Upper, Midway and Lower Basins. In these areas there is evidence of violent reactions immediately following the shock and as time progressed it became apparent that many more subtle and delayed responses were being felt. Now, eight months after the disturbance many features are gradually returning to their former state.

Lower Basin:

We are fortunate in having a Park Naturalist's eyewitness account of the simultaneous eruption of three major geysers immediately following the main shock. Fountain, Morning and Clepsydra went into action and continued erupting all through the 18th at which time Fountain Geyser ceased. Periodic eruptions of Morning Geyser continued until September first and Clepsydra, eight months later is still in action.

Their pre-earthquake pattern had been a chain reaction started by Morning, followed by Fountain and terminated by Clepsydra. At times they have erupted independently.

"Earthquake Geyser," a new feature west of Fountain Geyser, was born of the tremors. For several days it erupted at frequent intervals and then gradually declined.

Some springs acquired new water supplies at the expense of others and Gentian Pool ebbed 41 inches and has taken seven months to resume its former status.



PLATE 29. Clepsydra Geyser, Lower Geyser Basin, still in eruption eight months after the earthquake. National Park Service photo (59-846)



PLATE 30. Gentian Pool, Lower Geyser Basin, showing drop in water level to expose thin ledges of geyserite that grew over the surface of the pool. National Park Service photo (59-989).

Celestine, Silex and Leather Pools became violently active and for a two week period were ejecting muddy water.



PLATE 31. Silex Spring, Lower Geyser Basin, in violent stage with boiling muddy water. National Park Service photo (59-823)

There were no immediate changes in the Fountain Paint Pots but by August 21 new mud pots began to form and more violent action cast mud beyond the guard rail and some of the vertical guard rail supports served as escape routes for steam thus converting them into miniature fumaroles.

New steam vents opened up in the parking area and because of the obvious changes and unpredictable pattern of activity, the old parking area was removed and a new one is being developed a short distance away. Geysers and hot springs had reclaimed a tract of land on which man had encroached.



PLATE 32. Fountain Paint Pots, Lower Geyser Basin, in state of post-earthquake rejuvenation casting mud beyond the guard rail.
National Park Service photo (59-829)



PLATE 33. Former Fountain Paint Pot parking area, Lower Geyser Basin, showing post-earthquake encroachment of fumaroles and mud pots in the parking area. National Park Service photo (59-827)

In the Firehole Lake area a random network of fissures developed in the alluvial cover, some with minor displacement, and totaling 9,072 feet in length.



PLATE 34. Earthquake fissures in alluvial cover near Firehole Lake in Lower Geyser Basin. National Park Service photo (59-782)

The well-known Great Fountain, White Dome and Pink Dome Geysers departed radically from their normal eruption intervals.

Interested park visitors will soon find that the Lower Basin provides some of the more dramatic evidence of an earthquake's effect on hydrothermal features.

Midway Basin:

Most of the springs in this basin became turbid and many lowered their water levels. Turquoise Pool ebbed eight feet and the bowl of Grand Prismatic was slightly tilted so that the overflow shifted to a predominately easterly direction. The exact change in level is not known but it is estimated to be between one-half and one inch.

Biscuit Basin:

The stellar attraction in this area has always been Sapphire Pool, a feature that has enthralled thousands of people over the years. Its pre-earthquake activity consisted of small eruptions about every 20 minutes and from the boardwalk it was possible to see steam bubbles form, rise, and dome the surface with umbrella-like bursts while the water ebbed away in discharge channels ringed with globular growths of geyserite.

All is different now. On the morning of August 18 Sapphire had become a steady geyser with murky water rising eight feet in the air. During the night of August 21 there was a major eruption followed by even more violent ones in the months that followed. Blocks of geyserite with weights estimated from 50 to 100 pounds were torn from the rim and cast up to 50 feet from the crater.



PLATE 35. Sapphire Pool, Midway Geyser Basin, in post-earthquake eruptive stage. National Park Service photo (59-1125)

Some of the eruptions of Sapphire can definitely be associated with aftershocks as recorded on the seismograph at Butte, Montana. It would be interesting to learn if Sapphire is an "earthquake thermometer" triggered into action by tremors emanating from one epicenter.

Upper Basin:

The Grand Geyser erupted the night of August 17 and then went into a state of dormancy and was believed to be an earthquake fatality. However, later in the season it resumed limited activity and in time may regain its former status.

After forty years of dormancy the Cascade and Economic Geysers began periodic activity and Giantess went into an unprecedent eruptive phase that lasted for over 100 hours.

Other well known geysers such as the Daisy, Riverside, Castle, Grotto and Oblong began playing on shorter eruptive intervals that persisted for the balance of the year. The Giant Geyser has remained dormant.

World famous Morning Glory Pool ebbed six inches, became murky, and has taken seven months to resume its former status.

On the 18th of August it was noticed that Old Faithful was playing on a more erratic schedule with successive long and short intervals. Old Faithful's average eruption interval from June to August 17 was 61.8 minutes. For the last ten days of December two hundred and fifty-five eruption intervals averaged out to 67.4 minutes. Apparently there is a delayed response here to the tremors of last August. Whether it will continue or not time alone will tell.

Forceful eruption of previously quiet hot springs, erratic eruptive intervals of geysers, ebbed pools, and turbid water conditions are all to be expected when a geyser basin is shaken by earth tremors. These basins are topographically low and veneered with a cover of glacial gravels that provide the porous medium for ground water circulation. Earthquake vibrations have altered these circulation routes opening up new channels and closing off some of the old.

An analysis of temperature and discharge measurements on several hundred springs shows a post-earthquake temperature rise of about 6° Fahrenheit and an increased discharge of about ten per cent. How long these conditions will persist we of course have no way of knowing.

SUMMARY

The review of Yellowstone geology emphasizes that this portion of the Rocky Mountains is an active earthquake area where mountain building forces are still at work. For the interested observer there is a multitude of evidence of dynamic earth processes from the geologic past to the present.

The 1959 earthquakes have left their impress on this region. To date we have found no evidence of fault displacements within the park with the exception of that area on the western boundary in the vicinity of Grayling Creek. Earthquake energy seems to have been channeled along old well-established faults and the major rockslides occurred along canyon walls where the rocks are jointed and deeply weathered. Fractures in the alluvial cover and in the siliceous sinter of the geyser basins appear to be surface phenomena and probably do not extend to any great depth. Future work of the U. S. Coast and Geodetic Survey will reveal what changes of level have occurred. Undoubtedly some of the earlier established elevations are no longer correct.

Rumors and tall tales are a common aftermath of every major earthquake. Yellowstone was no exception. It was reported in the press that Old Faithful Geyser, shortly before the main shock, put on a performance of power unequaled in the history of the park. Every eruption of this geyser is different and during any 24 hour period there are appreciable variations in height, interval and duration of play. It would be very difficult to correlate supposed unusual behavior of Old Faithful with events that preceded the earthquake. If caused by a minor foreshock then certainly the geyser should have been most erratic in the weeks that followed when aftershocks were being recorded daily. This is contrary to the facts.

The legendary material of seismology includes many stories of unusual animal behavior during the hours that precede a major earthquake. Some accounts must be considered as coincidence, others imaginative, and there may be a scientific explanation for some. It is true that animals are more sensitive to certain vibrations than humans and it is quite possible that they react to shocks imperceptible to man. There have been conflicting reports of water birds vacating the Hebgen Lake area shortly before the main shock. In attempting to evaluate these reports one might seriously question how many

people are observant of waterfowl activity at midnight? On the other hand I have heard that a gravimeter survey party had to cease operations on August 17 apparently because this highly sensitive instrument was being disturbed. Until more factual information is available the reader must tentatively draw his own conclusions.

On the more factual side there are well documented reports* of the stampeding of elk concurrently with some of the aftershocks and it seems likely that some bear may have been buried in rock slides in Madison Canyon. One bear was trapped in a cave in the Firehole Canyon and was observed on August 23 trying to dig his way out. D. R. Hearne, Maintenance Foreman, West District, was able to pry loose some of the rock and the bear emerged apparently unharmed but with a strong desire to quench a six day thirst.

* Earthquake Study File, Yellowstone Park Library.

A PREDICTION FOR THE FUTURE

We have seen mountains rise from the sea floor, volcanic action on a grandiose scale, and glaciation, earthquakes and hydrothermal activity as important factors in shaping the landscape of this national park.

It is always interesting to speculate on the geologic future. An erosion cycle is now in progress. Streams, under the relentless pull of the force of gravity are deepening and widening their canyons. The plateaus will gradually be reduced as the broad, flat interstream divides are narrowed, and eventually what is now plateau will change to a landscape of rugged topography with sharp knife-like divides separating the streams. If not interrupted by mountain building forces the cycle will continue toward an ultimate base leveling of the land with all topography reduced to a monotonously flat surface.

The future of Yellowstone's heat resources is less susceptible to prediction. We know that hot spring and geyser activity dates back to a time before the glacial epoch and that within historic times no measurable decline in thermal activity has been detected. Could the increased heat flow in the geyser basins since the earthquakes be caused by a warming up of the magmatic hearths and therefore indicate a trend toward renewed volcanic action? Or, is the heat increase due only to agitation of the fracture systems underground permitting a freer circulation of water and magmatic gasses? Careful observations in the years ahead should provide the answer. Certainly we can rest assured that park visitors for generations to come will see "living geology" in Yellowstone but it will be different from that of today.

If we could imagine a movie camera timed so that the shutter clicked once every one hundred years, then it would take a reel of film almost one mile long to document the history of the earth. The geologic changes that man has seen in Yellowstone since its discovery would represent but one frame in the most exciting story ever filmed.

When viewed in this perspective, one earthquake that seems so catastrophic to us in recorded history is seen as but one pulse beat in the endless sea of time. Accordingly one can see how foolish it is to ask, "Will there be another earthquake?" Of course there will, but neither the time nor the place can be predicted with certainty. Without earthquakes we would not have the Yellowstone as we know it today.

GLOSSARY

Brief, simplified definitions of words that may not be familiar to some readers. More precise definitions can be found in any standard geology text book.

Agglomerate — explosive volcanic fragmental rock composed mostly of rounded or slightly angular particles greater than 32 mm. in diameter.

Algae — simple forms of plant life that are the predominant source of brilliant coloration seen in run-off channels of many hot springs and geysers.

Alluvium — stream deposits of sand and gravel.

Andesite — fine-grained igneous rock intermediate in composition between granite and basalt.

Aquifer — a stratum of rock or deposit of sand and gravel capable of transmitting water.

Basalt — a fine-grained, dark colored extrusive igneous rock.

Batholith — a large intrusive mass of igneous rock that increases in size as it extends downward and has no determinable floor. They have surface exposures greater than 40 square miles.

Block faulting — where large blocks of rock, bordered by faults on opposite sides, are either elevated or depressed.

Breccia — a fragmental rock consisting of larger particles than ash or tuff, but formed similar to them by showers of volcanic debris. There are other types of breccia.

Dolomite — a sedimentary rock consisting of calcium magnesium carbonate and usually formed from limestone by replacement processes.

Fault scarp — the cliff formed by a fault.

Geyserite — common deposit of the geyser basins, usually opaline silica.

Glacial drift — sediment deposited by glaciers.

Gneiss — a coarse-grained metamorphic rock that is distinctly banded.

Graben — depression formed by subsidence of a block of rock between normal faults.

Granite — a coarse-crystalline, light-colored, intrusive igneous rock.

Gravimeter — an instrument for measuring variations in magnitude of earth's gravitational field.

Igneous — formed by solidification from a molten state.

Kaolin — a rock composed essentially of clay minerals. Formed in Yellowstone by chemical alteration of feldspars in rhyolite.

Lopolith — a large floored intrusive that is centrally sunken into the form of a basin.

Magma — molten rock beneath earth's surface. When magma flows out on surface, it is called lava.

Normal fault — high angle fault formed by tension rather than compression.

Obsidian — a natural volcanic glass, usually a variety of rhyolite that has cooled rapidly.

Overthrust fault — a low angle fault formed by compression.

Perlite — a volcanic glass with numerous concentric cracks which give rise to perlitic structure.

Petrography — a branch of geology concerned with the systematic description and classification of rocks.

Pumice — cellular glassy lava usually composed of rhyolite.

Rhyolite — an extrusive igneous rock, fine grained, light in color, with same chemical composition as granite.

Schist — a metamorphic rock with foliated structure, split in thin irregular plates.

Tillite — unsorted and unstratified glacial sediment that has been cemented into a solid mass.

Travertine — a form of calcium carbonate deposited from solution in ground water.

Tuff — a deposit of volcanic ash compacted and cemented to form a solid rock mass.

Welded tuff — a dense form of rhyolite composed mainly of fragmented glass shards that have been welded and fused into solid rock. Their mode of emplacement is unknown. Some believe they are explosive and the result of settling; others believe they are formed as froths or avalanches. Thin section analysis under a petrographic microscope reveals their welded structure.

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PLATE 37. Map of earthquake area with numbered sites keyed to the text



Scale 1:250,000
CONTOUR INTERVAL 200 FEET
TRANSVERSE MERCATOR PROJECTION
5 0 5 10 15 20 25 30 Statute Miles
5 0 5 10 10 15 20 25 30 Kilometers
5 0 5 10 10 15 20 25 30 Nautical Miles

L.P.B.

PLATE 36. Map of Yellowstone Park and environs showing relationship of faults to earthquake epicenters and including seismic history of the park from 1871 through 1959

